Low-Bandgap Thermophotovoltaic System Design

Dale R. Burger and Richard C. Ewell, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109

Abstract

This system design of a thermophotovoltaic (TPV) module is based upon low-bandgap photovoltaic cells. The following technical areas are addressed: (1) System design including determination of module geometry and heat transfer, module size and configuration, array size and configuration, cooling water power requirements, module materials, and properties of the TPV cell cavity including the emitter and cell optical properties, cell mounting and cell wiring; (2) Determination of optical parameters including emitter spectra and emitter filtering options; and (3) Determination of the module power density.

Background

The concept of TPV energy conversion dates back more than 20 years (White, 1961 and Wedlock, 1963). It has been shown that the idealized TPV collvc.lie] is capable of very high efficiency (Wedlock, 1961). Much of the early research was on silicon cell based systems where the sun (Wedlock, 1963), fossil fuels (Haushalter, 1966), or radioisotopes (Gritton, 1965) provided the input energy. Several investigations of germanium photovoltaic calls for TPV have appeared (Kim, 1969 and Keith, 1972). There has been recent work on a radioisotope powered GaSb TPV system (Day, 1990).

System Design

The design of this TPV system included everything from the heat source down to the TPV cell mechanical parameters. Work previously reported but not published (Ong, 1992) discusses the details of the TPV substrate and cell fabrication. The baseline system design parameters were: source temperature range - 866K to 1255K (1100 °F to 1800 °F); maximum working pressure - 6.9 MPa (1000 psi); heat transfer coefficient - 5678 W/m^2-K; desired power density - 0.6 kW/l; and desired TPV conversion efficiency - 20%. Using these values the heat transfer, system configuration, material, and optical details were derived.

Heat Transfer

Heat Transfer Requirements - Heat transfer from the emitter to the TPV cell will be entirely by radiation. If the TPV cell has a band-gap of 3.3μm (this corresponds to the bandgap of InAs) and the system is operated at its maximum temperature (1255K) then the integral of Planck's law from 0.6 to 3.3 microns gives a blackbody radiated energy of 7.1W/cm^2. This is the maximum heat energy available for conversion assuming no losses. If all energy outside of the useful range is included, the heat transfer requirement would essentially double to about 14 W/cm^2. A reasonable maximum heat transfer requirement would then be about 10 W/cm^2 assuming limited losses and a surface emittance of less than 1.

Input heat by solids was ruled out due to design considerations, therefore, only gaseous and fluid heat transfer systems are considered in the discussion below.

Gaseous Heat Transfer - A preliminary look shows that a gaseous heat transfer medium (steam) at 6.9 MPa and 1255K will be off most steam tables. Using safety as a consideration, steam and other gaseous media were ruled out.

Fluid Heat Transfer - Organic liquid compounds generally will not be thermally stable at the operating temperature range. Thus only two types of fluid media were considered - liquid metals and inorganic compounds. The liquid metals were not favored due to safety reasons but are included here for the sake of completeness.

Liquid Metals - In the operating temperature range there are seven metals which are liquid at atmospheric pressure: Li, Ga, In, Sn, Tl, Pb and Bi. Sodium is just out of range at the high end, but can be included, if lightly pressurized. There are many binary alloys which could be used over the temperature range, but only data for NaK was sought due to time limitations. Thallium is very toxic and indium and gallium are expensive so these metals were dropped. Bismuth, lead and tin all have low specific heat values and limited easily available data. The remaining three metals have heat transfer data that is easily found in the literature: lithium, sodium, and sodium/78% potassium eutectic alloy.

Lithium has the highest specific heat of the three liquid metals, however a calculation of heat transfer requirements showed that this was not a decisive factor. Since lithium is extremely reactive and difficult to handle, it was dropped from consideration. There was no stated need for a low melting point so the sodium/potassium eutectic alloy (Na/78%K) was not selected. A possible safety problem from a potassium oxide explosion was an additional consideration. By elimination, sodium was chosen as the candidate input heat transfer fluid even though it must be pressurized to about 0.2 MPa (30 psi) at the high temperature end. Tin is the best alternative if system weight is not a problem or safety is important.

Inorganic Compounds - There are at least fifteen possible simple inorganic compounds which are liquid at atmospheric pressures throughout the desired temperature range and which are not likely to thermally decompose. Some compounds such as samarium iodide are too expensive to be considered. Other compounds such as cadmium chloride are too toxic. If these two criteria are applied, then there remains only six simple inorganic compounds: CuCl, B_2O_3, LiBr, LiI, KOH, NaOH. All of the halogen containing compounds are questionable since the selected high temperature tubing materials are attacked by halogens but form stable, high temperature oxides. The remaining three compounds are commonly used materials so their thermodynamic properties were sought.

All three compounds have adequate thermal properties. Both hydroxides are very likely to be corrosive. The vapor pressure for boron oxide was not listed in the reference handbooks, so this property is still in question. Overall, boron oxide may prove to be the least troublesome compound for heat transfer. However, material properties of boron oxide would need to be determined in order to properly evaluate this material.

System Configuration

Modular Tube Arrangement - TPV cell efficiency varies with radiation temperature due to changes in the emission spectrum and radiation intensity. A counterflow heat transfer system would therefore see a large temperature change along the length of the tube. This large temperature change would cause each cell in a series string to produce a different output current and thus the performance of the series string would be degraded to the current of the least efficient (lowest emission temperature) cell.

In order to transfer heat at equal temperatures to a large number of TPV cells it was decided to use a cross-flow tube bank design for the system (see Fig. 1). The highest row of tubes shown in the figure will all see the same inlet temperature essentially all around their circumference and all along their length. The next lower row of tubes will have a lower input temperature and so on to the bottom of the tube bank where the outlet temperature will be seen. A 10 by 10 tube bank was selected from heat transfer tables (Parker, 1969, p. 263) for calculation and representation purposes. In order to maintain a predictable heat transfer rate and to minimize volume, the 10 x 10 tube bank should be arranged as a staggered equilateral triangle having a pitch to diameter ratio of 1.25 (the smallest recommended ratio) which results in a tube-to-tube gap of 1 cm. This is just a little larger than the minimum recommended 0.64 cm (0.25") spacing (Kreith, 1973, p. 483).

Modular Tube Size and Shape - A tube outside diameter of 4 cm was selected to allow a hexagonal inner tube with 1 cm faces and to provide some room for optical concentration at a later date (See Fig. 2). A module tube length of 1 m was selected to allow adequate series string voltage. This tube is exposed to the drag from the circulating heat transfer medium. The coefficient of drag for a cylinder was found from a graph (Parker, 1969, pg. 121). Calculations show that the drag (130 N) at operating temperatures on this length of cylindrical tubing would only deflect the tube by 0.0079 cm (0.0031").

A cylindrical geometry was selected because of its ability to withstand the pressure differential between the vacuum inside and the pumped liquid outside. A cylinder also minimizes the wall thickness, which in turn reduces the mass of the module as well as improving heat transfer. The outside of the tube was left as a cylindrical surface since any fins or irregularities cause large temperature changes due to restricted flow. The inside surface of the tube was also left as a cylindrical surface so as to simplify analysis, however, the use of internal fins should result in improved surface emittance.

Materials

Emitter Tube Materials - A liquid metal system was chosen as a baseline. However, other materials choices may be made if another baseline heat transfer medium is selected. There are only two well- characterized metal alloy systems for use with corrosive liquid alkaline metals while exposed to high temperatures: Nb/1%Zr, and T-111 (Ta/8%W/2%Hf). When the working pressure constraint of 6.9 MPa (1000 psi) is applied, the stronger, T-111 alloy was selected since it results in a tubing wall thickness of only 1.14 mm (0.045") versus 2.79 mm (0.110") for Ni/1%Zr. The use of these alloys with alternative heat transfer media, such as boron oxide, awaits determination of the properties of B_2O_3 over the operating temperature range.

TPV Cell - The availability of highly uniform, good quality, single crystal substrates of low band-gap photovoltaic materials is limited at this time. As a result, a cell size of 1 cm x 1 cm has been chosen in order to simplify procurement of cells. This selection will cause high assembly labor costs but this is balanced by lower material costs.

Cell Cavity Optical Properties - The emitter surface will be selected from a number of different materials which are capable of selective emission such as: specular metal with a thin film coating of silicon dioxide; or specular metal with a thin film coating of a rare earth oxide (preferably holmium).

The TPV cells are located on the outside of a specially extruded aluminum tube which has 1 cm facets. The cell front surface could be textured for optimum absorption rather than polished although polished surfaces are easy to fabricate. The front surface could have a visible/near-IR antireflection coating which becomes a reflecting surface in the middle-IR. The effect would be that of a high pass filter. The back surface of the cell will be highly polished since it must be a very good reflector of infrared photons with wavelengths longer than the bandgap.

TPV Cell Mounting - The TPV cells will be mounted on each facet along the axis of the inner tube. Since the cells and the inner tube will not undergo any temperature extremes, it is possible to use silver epoxy for good heat conduction. The surface of the inner tube may be anodized to produce an insulating surface with little thermal resistance.

Wiring - Each facet of the inner tube

will be wired as a series string. The open circuit voltage of each cell is expected to be approximately 0.18 V for InAs cells. If there are one hundred 1 cm cells on a 1 m tube, then the resultant series string output should be about 18 V. If the total useable radiated power is 7 W/cm^2 (0.6-3.3μm) and all of this power is directed to the cell then the output current would be about 15 amperes, assuming a 20% cell was available. Output for all six facets of the tube could then be as high as 972 W for the high temperature bank of tubes using a fill factor of 0.6.

Optical Parameters

Emitter - The emission spectrum will depend upon which emitter design is chosen. An emitter made by coating a sheet of polished tungsten with silicon oxide should have spectrally selective absorption and emission (Ref. 4, pg. 149). An emission spectrum of thin film rare earth oxide on specular metal has not been found in the literature but is of interest.

Filtering - The concept of filtering has to be discussed in context with the rest of the module design. First, the use of selective emitters which has already been discussed, can be viewed as a form of filtering. Second, the use of a high-pass antireflective coating on the cell surface is definitely a form of filtering. Third, the use of a discrete filtering element located in the space between the emitter and the cell is a possibility, but it raises serious mechanical design problems: filter absorption losses and heating, filter band width for different emitter temperatures, filter suspension and end plate sealing, and fragility.

Module Power Density

Efficiency vs. Power Density - The TPV cell efficiency is predicted to list with increasing power density incident on the cell surface (Sew Fig. 3). If optical concentration were to be implemented, efficiencies as high as 23% are attainable in this particular system. An effective concentration of approximately 9x is necessary to obtain a predicted efficiency of 20%. The feasibility and the methods of implementing such concentration are still to be determined.

Power Density vs. Heat Transfer Rate - The chosen fluid-to-module heat transfer coefficient is .5678 W/cm^2-K. In order to achieve the maximum black body emitter radiated power of 7.012 W/cm^2 (0.6-3.3μm) at 1255K, there will have to be a temperature drop from the fluid to the emitter tube of 12.35K. This poses no problems.

Power Density vs. Temperature - TPV cell efficiency and emitter surface radiation both decrease with decreasing temperature. At 1255K and 20% TPV efficiency the power density is .42 kW/l for the top bank of tubes and the outlet temperature is assumed to be about 1170K. If the corresponding outlet temperature is the minimum allowed (866K), then the lower bank temperature would be about 900K and the power density would be only about 0.12 kW/l.

Pumping Losses - Pumping losses are charged against overall system efficiency so these losses must be kept small. The power required to pump the liquid metal and water for the 10 x 10 x 1 m tube bank is approximately 530 W_e compared to the estimated 97.2 kW output from the TPV cells in the bank.

Summary

A system design was made of a thermophotovoltaic (TPV) module and a corresponding array of modules to accommodate low- bandgap TPV cells. The system was intended to be practical for future fabrication. The array includes one hundred tubes (modules), which are arranged in a cross-flow tube bank configuration in order to transfer heat at equal temperatures to the large number of TPV cells. Each module consists of two concentric tubes. The outer, cylindrical tube includes the emitter surface and outer shell material; the inner, hexagonal tube includes the TPV cells, which are maintained near room temperature by cooling water within the tube. The maximum estimated electrical output for one module is 972 W and the 100 tube bank is 97.2 kW.

Acknowledgements

The work described in this paper was performed by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration, and was supported by the Department of Energy.

References

Day, A. C., Horne, W. E., and Morgan, M. D. *Proc. of 21st IEEE PVSC, 1990,* pp. 1320-1325

Gritton, D. G. and Bourke, R. C. *Adv. Energy Conv., v 5, 1990,* p. 119

Haushalter, R. W. *Final Report, Contract DA-44-009-AMC-622(T)(MERDC), Gen. Motors Def. Res. Labs., June 1966.*

Keith, E. and Guazzoni, G. *Proc. 25th Power Sources Symp.,May 1972,* pp. 106-109

Kim, C. W. and Schwartz, R. J. *IEEE Trans. on Electron Dev., ED-16, n 7, July 1969,* pp. 657-663.

Kreith, F. *Principles of Heat Transfer, 3rd Ed.,* Intext Educ. Pub., New York, 1973.

Ong, T. P., "Low-Bandgap Thermophotovoltaic Development Interim Report - Phase IB, Cell Modeling and Design, Aug. 18, 1992.

Parker, J. D., Boggs, J. H., and Blick, E. F., *Introduction to Fluid Mechanics and Heat Transfer,* Addison-Wesley, 1969.

Wedlock, B. D. *Proc. IEEE, v 51, May 1963,* pp. 694

White, D. C., Wedlock, B. D., and Blair, J., *Proc. of 15th Ann. Power Sources Conf., Atlantic City, NJ, May 1961.*

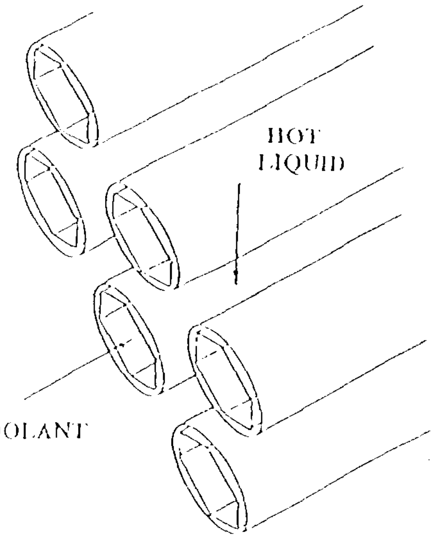

Fig. 1 Cross Flow Module Layout

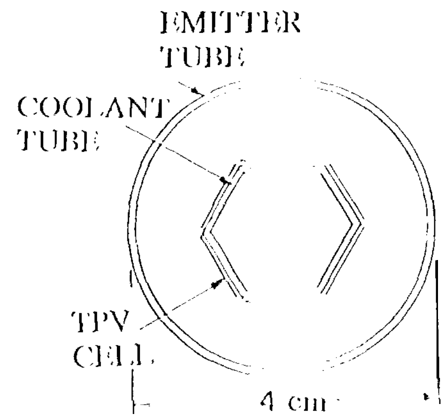

Fig. 2 Typical Module Tube Geometry

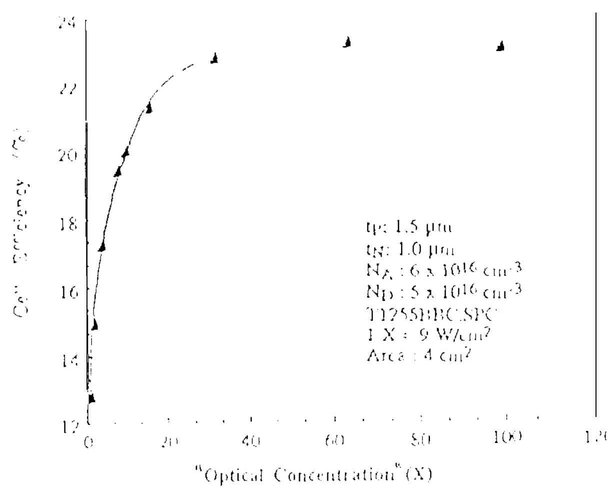

Fig. 3 InAs Cell Efficiency vs. Incident Emission